X-913-75-26
Preprint

NASA TM X- 70840

SEASONAL STREAMFLOW ESTIMATION EMPLOYING SATELLITE SNOWCOVER OBSERVATIONS

(NASA-TM-X-70840) SEASONAL STREAMFLOW ESTIMATION EMPLOYING SATELLITE SNOWCOVER OBSERVATIONS (NASA) 39 p HC $3.75 CSCL 08L

N75-18695

Unclas
G3/43 13272

A. RANGO
V. V. SALOMONSON
J. L. FOSTER

FEBRUARY 1975

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-913-75-26
Preprint

SEASONAL STREAMFLOW ESTIMATION EMPLOYING SATELLITE SNOWCOVER OBSERVATIONS

A. Rango and V. V. Salomonson

NASA/Goddard Space Flight Center

Greenbelt, Maryland

and

J. L. Foster

Geology Department/University of Maryland

College Park, Maryland

February 1975

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland

CONTENTS

TABLES

ILLUSTRATIONS

SEASONAL STREAMFLOW ESTIMATION EMPLOYING SATELLITE SNOWCOVER OBSERVATIONS

A. Rango and V. V. Salomonson

NASA/Goddard Space Flight Center

Greenbelt, Maryland

and

J. L. Foster

Geology Department/University of Maryland

College Park, Maryland

February 1975

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland

SEASONAL STREAMFLOW ESTIMATION EMPLOYING SATELLITE SNOWCOVER OBSERVATIONS

A. Rango and V. V. Salomonson

NASA/Goddard Space Flight Center

Greenbelt, Maryland

and

J. L. Foster

Geology Department/University of Maryland

College Park, Maryland

ABSTRACT

Low resolution meteorological satellite and high resolution earth resources satellite data have been used to map snowcovered area over the upper Indus River and the Wind River Mountains of Wyoming, respectively. For the Indus River early Spring snowcovered area was extracted and related to April through June streamflow from 1967-1971 using a regression equation ($r^2 = 0.91$). Prediction of the April-June 1972 streamflow from the satellite data was within three percent of the actual total. Composited results from two years of data over seven Wind River Mountain watersheds indicated that LANDSAT-1 snowcover observations, separated on the basis of watershed elevation, could also

be related to runoff in significant regression equations. It appears that earth resources satellite data will be useful in assisting in the prediction of seasonal streamflow for various water resources applications, non hazardous collection of snow data from restricted-access areas, and in hydrologic modeling of snow-melt runoff.

SEASONAL STREAMFLOW ESTIMATION EMPLOYING SATELLITE SNOWCOVER OBSERVATIONS

A. Rango and V. V. Salomonson

NASA/Goddard Space Flight Center

Greenbelt, Maryland

and

J. L. Foster

Geology Department/University of Maryland

College Park, Maryland

INTRODUCTION

The melting of the snowpack in the Spring is the source of greater than 50 percent of streamflow in most areas of the Western United States (Committee on Polar Research, 1970 and Rooney, 1969). For example, about 75 percent of the runoff in the Colorado River originates from snowmelt in key basins that represent only 13 percent of the contributing land area (U. S. Department of Interior, 1970). The early prediction of the amount of runoff to be derived from the snowpack allows more efficient utilization of the limited water supply for power generation, irrigation, flood control, domestic and industrial water supplies, and recreation. Historically, the Soil Conservation Service has prepared seasonal snowmelt runoff forecasts for western river basins that have been extremely useful for water management purposes. For the Western United States, error in seasonal runoff forecasts prepared on 1 April ranges from 7 to 40 percent, with an average of approximately 18 percent (U. S. Department of Interior, 1974). These discrepancies are due to forecasting errors inherent in the procedures used and to errors resulting from variations in the weather after 1 April. The forecasting errors result from uncertainties in point measurements of snow water equivalent which are commonly used as indices of basinwide snowmelt runoff in prediction equations. The errors in predicted runoff tend to be largest in years of unusually heavy or light snowpack accumulation.

Observation of the areal extent of the snowpack has long been recognized as an important (but difficult to obtain) hydrologic parameter related to both the average snowpack water equivalent and the snowmelt-derived runoff. The U. S. Army Corps of Engineers (USACE) in the Northwest and the Salt River Project in Arizona have in the past flown low altitude missions in order to measure snowcover areal extent to aid in their runoff prediction responsibilities. The rate at which the snowcover depletes is an index which is inversely related to the snow water equivalent and the generated snowmelt runoff. As the snow leaves the low elevations of the watershed, the hydrograph begins to rise and continues to do so until the snowpack area reaches a critical value where meteorological snowmelt conditions cannot produce ever increasing amounts of runoff. The hydrograph then begins to recede until the remaining snowpack disappears and the runoff is maintained by baseflow. The slower the snowline retreats up the watershed to the elevation where the hydrograph starts a downward trend, the greater the resulting runoff volume and, usually, peak flow.

Although high resolution, temporal areal snowcover data are important, it has been difficult for various user agencies to obtain these data on a regular basis. As a consequence very few runoff prediction techniques are compatible with snowcovered area inputs. Since 1972, however, two satellites possessing relatively high resolution sensors have been regularly observing snowcovered area. LANDSAT-1 (previously known as ERTS-1) has been providing 80 m resolution, multispectral visible and near infrared observations over a 185 km × 185 km area as often as once every 18 days. NOAA-2 (3 and 4) has provided daily visible and thermal infrared observations, but with a resolution of about 1 km. The work reported on here using small watersheds has used data from LANDSAT-1 only.

The purpose of this study was to examine the possibilities of seasonal streamflow estimation employing satellite snowcover observations, both from existing long term, low resolution meteorological satellite data and from the newly available high resolution multispectral satellite information. There are various reasons why satellite snowcover data, if proved effective, would be desired by water resources agencies in preference to aircraft or ground derived data. Fatal accidents have occurred during both ground-based and aerial snow surveys, and, as a result, the safety factor would optimumly increase with unmanned space surveys. Wiesnet and McGinnis (1974) have shown that snow extent mapping is both six times faster from LANDSAT-1 imagery than from high altitude aerial photographic surveys, and that the cost of snow maps produced from LANDSAT-1 is about one-two hundredth the cost of the simplest maps made from aircraft surveys. In addition, the procedures for mapping snow-cover from space and its excellent comparison with conventionally derived snow-cover maps have been documented by many investigators. Such techniques and results have been compiled in handbook form by Barnes and Bowley (1974). Ground-based snow observations are gradually being restricted in mountainous areas as a result of marked increases in wilderness areas developed under the 1964 Wilderness Act. Because these areas are continually increasing and accessibility to high alpine snowpack areas is continually decreasing, satellite observations may be the way to serve both the environmentalist's and the snow surveyor's objectives. Even in nonrestricted areas snow data are difficult to obtain from remote regions and often too few and perhaps unrepresentative samples are available. Remote sensing provides a reasonable way to monitor snow in these remote regions, and the data may even eventually be used to extrapolate conventional point data more effectively over entire watersheds. Finally, some watershed numerical models are beginning to require the input of the observed snowcovered area. Satellite derived snowcover seems to be a logical source for satisfying such requirements in the future.

Even though it has been shown that snow extent can be accurately measured from LANDSAT-1 imagery (Barnes, Bowley, and Simmes, 1974), there has been some question about usefulness in terms of predicting snowpack yield or seasonal runoff in view of the fact that only the area covered by snow, and not snow depth or water equivalent, is observed. This is true of all visible, near infrared, or thermal infrared sensors, no matter what their resolutions. Only two years of snowcover versus runoff information exist for LANDSAT-1 (or NOAA-2), and this is generally not a sufficient number of observations to indicate the validity of any empirical statistical relationship that might appear to exist between snowcovered area and runoff. As a result, longer duration data than presently exists for LANDSAT-1 had to be obtained.

Using the Image Dissector Camera System on Nimbus 3 and 4, Salomonson and MacLeod (1972) mapped the areal extent of snowcover over the Indus River Basin in the Western Himalayas. The areal extent of snowcover for 1969 and 1970 was plotted so as to relate a decrease in the snowcover to an increase in the mean monthly runoff. The results by Salomonson and MacLeod (1972) indicated that some success might be achieved in predicting the seasonal runoff volume or the level of peak discharge if the snow areal extent and location of the snowline in late winter or early spring were monitored by satellite. Because several years of meteorological satellite data now exist, this research has been extended to cover six years of snowcover versus runoff and to test whether an empirical relationship of satistical significance was evident. Additionally, LANDSAT-1 data have been used over seven watersheds in the Wind River Mountains of Wyoming to determine if any of the relations prevalent on the Indus River might similarly exist on relatively small watersheds.

STUDY AREAS AND DATA SOURCES

The Indus River Basin above Attock, Pakistan covers approximately 260,000 km^2 with elevations ranging from 305 m at the streamgage (IHD Station HD-23) to over 8,500 m in the Hindu Kush, Karakoram, and Himalayan Mountains. Portions of the basin are located in Pakistan, Afghanistan, India, and China. At the time of the study, no major diversions for water resources projects occurred above the streamgage thus making the recorded flow indicative of the snowmelt runoff. Watersheds this large without significant flow diversions do not exist in the United States. Streamflow data were received from the Pakistan Water and Power Development Authority from 1967-1972. The 4 km resolution Advanced Vidicon System on various ESSA satellites provided coverage for the years 1967-1972, and similar resolution Scanning Radiometer data from NOAA satellites are available for 1973 and 1974. One of the world's largest reservoirs, the Tarbella Dam, is being constructed 64 km above the gage at Attock and may affect flow measurements as early as 1973.

The Wind River Mountains are located in west central Wyoming and range in elevation from 2000-5000 m. Two major rivers rise out of the Wind River Range, namely, the Green and Wind Rivers, and flow diversions for irrigation are numerous; only in the extreme headwaters or on small tributary streams do relatively unimpaired records exist. Seven such small watersheds were selected ranging in area from 200 km^2 to 1200 km^2. Preliminary streamflow records for 1973 and 1974 were supplied by the U. S. Geological Survey for the seven streamgages. Eighty meter resolution LANDSAT-1 multispectral scanner data in the 0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1 μm wavelength bands were available from July 1972 to the present. Additional data included high altitude U-2 color infrared photography over the watersheds in 1974 and U. S. Soil Conservation Service ground snow survey measurements for 1973 and 1974.

METHODS

Images over the Indus River Basin from April through July were selected from 35mm microfilm rolls of available ESSA and NOAA satellite data. The data were scanned on a daily basis and approximately one clear image per week over the Indus Basin was selected and made into a 35mm positive slide. The 35mm slides were projected onto a 1:2,000,000 scale aeronautical chart of the basin and the scale of the image adjusted using a zoom lens to fit the chart. The amount of snowcover was then mapped from the chart onto a transparent overlay and the percent of snowcovered area calculated with a planimeter. Due to a lack of detail on maps of this scale and the large size of the basin, the snowline altitude was not calculated for the Indus Basin.

The areal extent or percent of snowcover for the entire season can be plotted so as to relate a decrease in snowcover to an increase in weekly or monthly runoff. In order to better simulate a prediction situation, however, percent snowcover area from satellite images between 1-15 April of each year were averaged and plotted against the seasonal runoff occurring from 1 April to 30 June. A regression equation for the years 1967-1971 was developed initially. When the 1972 snowcover data was obtained, the regression equation was used to predict the seasonal streamflow. Subsequently, the 1972 snowcover and runoff data were incorporated into the regression relation.

LANDSAT-1 imagery was obtained for each pass over the Wind River Mountain watersheds for 1973 and 1974 in the standard photographic, single-band 1:1,000,000 scale positive transparency format. Generally, only the 0.6-0.7 and 0.8-1.1 μm black and white transparencies were used for snow-cover area extraction. The snow was mapped using the LANDSAT-1 transparencies, U.S. Geological Survey 1:250,000 scale topographic maps, and a zoom transfer scope. The zoom transfer scope with its mirrors, lenses, and scale adjustments allowed the 1:1,000,000 scale image to be superimposed optically onto the map so that drainage areas could be delineated and snowlines mapped at a scale of 1:250,000.

Once the snowline was located, the percent and area of snowcover within a given watershed was calculated with the aid of a planimeter. The snowline altitude, if desired, could be determined by using the Equivalent Snowline Altitude (ESA) method (Meier, 1973). The ESA method is based on an area-altitude function whereby for a given mountainous drainage basin, the percent of area above various elevation contours is planimetered and the percent of basin area is plotted against the corresponding elevation. Thus, when the percent of snowcovered area is measured, the elevation of the snowline can be obtained by referring to the ESA function for that particular basin.

Next, the average snowcover area depletion for all seven Wind River Mountain watersheds was plotted and graphically related to increasing runoff for 1973 and 1974 separately. Additionally, the same data were separated into two groups of watersheds based on mean elevation and replotted in the same way. Subsequently, the percent snowcovered area on 15 May in 1973 and 1974 for each watershed was plotted versus the 15 May-31 July seasonal runoff for the high elevation watersheds (6 data points) and the low elevation watersheds (8 data points). A regression analysis was performed on these two data sets assuming that the watersheds within each elevation group were very similar in all respects. Factors that could contribute to the total regression variance, however, were recognized as differences in watershed shape, percentage of forest cover, and mesoscale meteorology and climatology. In order to account for variations in watershed size and subsequent runoff, the streamflow data were converted to discharge per unit area values.

LANDSAT-1 snow mapping was facilitated by examining false color composites employing 0.5–0.6, 0.6–0.7, and 0.8–1.1 μm data taken during the summer so that forested and bare rock areas could be located and positioned. The 0.6–0.7 μm band was used to obtain snowcover area measurements for the runoff relations, and snow extent measurements using the 0.8–1.1 μm band were compared to the 0.6-0.7μm band area measurements in order to estimate areas of metamorphosed snow, i.e. snow either actively undergoing melt or snow that had been melting the previous day but was refrozen at the time of satellite over pass. Rationale for this assumption is provided by H. W. O'Brien and R. H. Munis (unpublished data, 1974). Finally, high resolution U-2 aircraft data for 1974 over three of the watersheds was areally compared to snowcover areas obtained from temporally similar LANDSAT-1 passes.

RESULTS AND DISCUSSION

Figure 1 presents an example of the annual variation in snowcover at the beginning of April over the Indus River Basin as observed from ESSA 9. Early April was chosen as the beginning of significant snowmelt and the index time for predicting the April-June seasonal runoff. Figure 1 shows that on 4 April 1969 the snowcover was heavy and covered 60 percent of the basin. Resulting seasonal runoff was about 29.6 million acre-feet ($3.65 \times 10^{10} m^3$). On 3 April 1971, however, the snowcovered area was 44 percent and the subsequent seasonal runoff totalled approximately 25 million acre-feet ($3.08 \times 10^{10} m^3$). The scenes shown in Figure 1 were indicative of the 2-3 scenes that were averaged between 1-15 April of 1967-1971, and the snowcover area mapping was easily accomplished.

The 1967-1971 average percent basin snowcover for 1-15 April was then plotted against the 1 April - 30 June corresponding measured runoff in acre-feet (m^3) and a straight line relationship was evident. A significant linear regression equation was derived using these points which took the form $R = (.288S + 11.98) \times 10^6$ where R is the April to June yield in acre feet and S is the percent basin snowcovered. The coefficient of determination, r^2, for this equation is 0.91 (significant at the one percent level) and the standard error was 5 percent of the mean seasonal yield. When the 1972 satellite snowcover data became available, the above regression equation was used to predict the April-June 1972 seasonal runoff. The satellite-measured 1-15 April average snowcover was 67.3 percent and the predicted April - June yield was 31.5 million acre-feet (3.88×10^{10} m^3). When the 1972 streamgage records were obtained, the actual April-June yield was determined to be 32.3 million acre-feet (3.98×10^{10} m^3). The difference between predicted and actual yield was only 0.86 million acre-feet (1.06×10^9 m^3) or within three percent of the actual seasonal yield. Figure 2 shows the 1967-1972 snowcover versus seasonal yield data plotted and a new regression line obtained by incorporating the 1972 data into the relation. The new equation is $R = (.300S + 11.52) \times 10^6$ with r^2 being 0.92 (significant at the one percent level) and the standard error again equalling 5 percent of the mean seasonal yield.

These results indicate that even though snow depth or water equivalent are not directly measured, it appears that areal snow extent is an adequate index parameter for aiding in the prediction of seasonal runoff on a large data-sparse watershed. Because watersheds of this size and relatively undisturbed nature are not commonly found in areas such as the United States, the same kind of test was applied to several very small watersheds in Wyoming using the high resolution LANDSAT-1 data.

Figure 3 is a 0.6-0.7μm view of the Wind River Mountains taken in August 1972 which delineates the seven watersheds selected for analysis. The Green, Pine, East Fork, and Big Sandy watersheds are in the Colorado River Basin, whereas Bull Lake, Dinwoody, and Wind are in the Missouri River Basin. More importantly, for this analysis, Wind River, Green River, East Fork River, and Big Sandy River were grouped as low watersheds with mean elevations less than 3050 m. Bull Lake Creek, Dinwoody Creek, and Pine Creek all had mean elevations in excess of 3050 m and were grouped as high watersheds. The smallest watershed under study was Pine Creek (200 km^2) and the largest was Green River (1200 km^2).

As an example of the kind of snowcover changes observed during the course of a year with LANDSAT-1, Figure 4 presents four 0.6-0.7μm views of the Wind River Mountains during the 1972-1973 snow season. The 6 August scene shows bare rock, late-lying alpine snow, and glaciers above the tree line during minimum snowcover. The 10 December scene illustrates total snowcover over the entire area with the darker tones indicating areas of forest cover over the snowpack. The 21 May and 8 June scenes are taken during the active snowmelt season and display the kind of changes detectable from one LANDSAT-1 pass to the next. To illustrate, in the 21 May scene Bull Lake Creek and Green River are 86 and 55 percent snowcovered, respectively. Because of persistent snowmelt during the 18 day interval between satellite passes, 8 June snowcover has decreased to 58 percent for Bull Lake Creek and 27 percent for Green River. Such clear imagery was common during the melt season, and only in a few instances was a particular watershed obscured by clouds during a LANDSAT-1 overpass in 1973 and 1974.

Comparison of LANDSAT-1 images on similar dates in 1973 and 1974 indicates that generally more snowcover exists in 1974 than 1973. Streamgage records show that more runoff occurred during the 1974 snowmelt season as a direct result. This is illustrated graphically in Figure 5 showing that during the major melt period from late April to late June snowcover percentages in 1974 were in excess of those in 1973. The 18 day total flow, in cfs/mi^2 (m^3/sec/km^2) plotted to correspond with each LANDSAT-1 pass, produces a 1974 peak considerably in excess of the 1973 value. Figure 6 shows the average snowcover depletion and runoff curves for 1973, but this time plotted on the basis of elevation. The low elevation watershed snowcover breaks off at a more rapid rate than the high elevation watersheds indicating the probability of a greater volume of snow on the higher watersheds. The resulting runoff, normalized for watershed area differences, bears out this hypothesis. A lower peak and total flow occurs on the low watersheds, and, additionally, the peak occurs two weeks earlier on the low watersheds than on the high watersheds.

Such graphical relationships are promising in that they show a positive qualitative relation between snowcover depletion and resulting runoff. A quantitative prediction of seasonal streamflow, however, is not possible using these curves. In an attempt to produce a quantitative snowcover-runoff relationship, i.e., a regression equation similar to that derived for the Indus River, the available data were treated as two different data sets based on elevation. In Figure 7 the percent snowcover on 15 May (S) is plotted against the seasonal runoff from 15 May-31 July (R) in cfs/mi^2 (m^3/sec/km^2) for the three high elevation watersheds for both 1973 and 1974. In order to increase the data base for a regression analysis, the three high elevation watersheds, although possessing some differences, were assumed to be alike enough to be treated as a single watershed. Six data points were thus available for the two years and the resulting regression was $R = 30S - 2198$ with a r^2 of 0.89 significant at the one percent level and a standard error equal to 13 percent of the mean seasonal yield (15 May-31 July). For the lower elevation watersheds, the same similarity assumption was made and the data plotted in Figure 8. The equation was $R = 5.8S - 156$ with a r^2 of 0.85 significant at the one percent level and a standard error equal to 14 percent of the mean seasonal yield. Although a crude estimate of seasonal runoff could be made for nearby watersheds using these equations based on only two years of data, the real importance of such relations rests in the fact that the changes in areal snow extent as observed from space are quantitatively related to snowmelt runoff and, as a result, indirectly to the volume of water on a watershed. With an adequate number of years of snowcover versus runoff observations on single watersheds, seasonal runoff predictions could be made from space. These data, if combined with conventionally gathered data used for streamflow forecasting, should be useful for reducing the errors associated with current prediction techniques. Because streamflow predictions are needed before the time of snowcover breakup - about 1 May in the Wind River Mountains - the satellite data could be used later in the snowmelt season to update and refine the earlier conventional predictions. The U. S. Department of Interior (1974) sponsored study has shown that such late season refinements may be worth considerable amounts of money for power generation alone. In the Southwestern United States snowpack areas snowcover breakup can be observed much sooner in the year and the satellite data should be even more useful for early runoff predictions.

Satellite snowcover data would be additionally important if they could be inserted into watershed models. The simple areal extent of snow is employed in some models now, basically for the correct application of energy balance equations, but a potentially even more useful parameter would be the area of the watershed snowpack currently or recently melting. Such data can potentially be obtained by comparing the 0.6-0.7 (Band 5) and 0.8-1.1μm (Band 7) wavelength bands on LANDSAT-1 as indicated in Table 1. Band 5 generally is assumed to delineate the total snowcovered area whereas Band 7 consistently indicated less snowcover. This difference, as shown for the seven Wind River Mountain watersheds in Table 1, was attributed to the reduced near infrared reflectance associated with melting or refrozen previously melting snow. Such information could be invaluable to models for refining the timing aspects of predicted snowmelt runoff.

In order to assess the resolution adequacy of using LANDSAT-1 for snow-cover mapping in the Wind River Mountains, high resolution (10m) U-2 aircraft flights were flown in 1974 at the approximate time of a LANDSAT-1 overpass. Table 2 presents a comparison of the U-2 flights on 24 May and 25 June with the LANDSAT-1 overpasses on 16 May and 21 June for the high elevation watersheds. Areal extent of snow from LANDSAT-1 corresponded closely to the high resolution aircraft data, with differences no greater than 4 percent of watershed area. Analysis of the data has indicated that the area covered by snow is adequately expressed in LANDSAT-1 0.6-0.7 μm data, and that snow-cover mapping using LANDSAT-1 is much faster because it is considerably less complicated than similar mapping with the very detailed U-2 imagery. Additional advantages of the LANDSAT-1 data include the facts that no mosaicking of the small watersheds is necessary and that flight logistics problems are at a minimum.

CONCLUSIONS

1. On large watersheds (10^5 to 10^6 km^2) where the flow is relatively unimpaired by reservoirs or water withdrawals, meteorological satellite snowcover observations apparently can be used in lieu of other snowpack parameters, such as depth or volume, to predict seasonal runoff if enough years of information exist.

2. On watersheds as small as 10 km^2 in areas with infrequent cloud cover during the snowmelt season, LANDSAT-1 data can be used to accurately measure the extent of snowcover and monitor its change with time. It seems to be possible to quantitatively relate the percent of the basin snowcovered on a given date to a measure of seasonal runoff on the small watersheds similar in nature to that performed on the large Indus River Basin. In the United States it is necessary to develop such relations on small watersheds in order to effectively predict streamflow at points above significant water diversions.

3. Because of the quantitative relations developed here it appears that satellite observed snowcovered area could be usefully employed as an additional seasonal runoff index parameter or as an input into certain hydrologic models. The advantage of such information is that they are non hazardous, easy to obtain data requiring no access to restricted wilderness or remote areas. In the Western United States, because of the significance of water stored in the form of snow for hydroelectric power generation, irrigated agriculture, and reservoir regulation, the importance and value of more accurate runoff information provided by satellite observations is very promising.

ACKNOWLEDGMENTS

We would like to thank Mr. M. Umar and Mr. K. Jawed of the Pakistan Water and Power Development Authority; Mr. D. J. O'Connell and Mr. J. F.

Wilson of the U. S. Geological Survey, Water Resources Division, Wyoming; and Mr. G. W. Peak and Mr. G. P. Clagett of the U. S. Soil Conservation Service, Casper, Wyoming for supplying streamflow and ground snow survey data necessary for conducting this study. Additionally, we acknowledge the high altitude aircraft support provided us by the Earth Resources Aircraft Project at NASA's Ames Research Center, Moffett Field, California.

REFERENCES

Barnes, J. C., and C. J. Bowley, Handbook of techniques for satellite snow mapping, Final Report, NAS5-21803, 95 pp., National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, 1974.

Barnes, J. C., C. J. Bowley, and D. A. Simmes, Mapping snow extent in the Salt-Verde watershed and the southern Sierra Nevada using ERTS imagery, in Proceedings of the Third ERTS-1 Symposium, NASA SP-351, vol. 1, pp. 977-993, U.S. Government Printing Office, Washington, D.C., 1974.

Committee on Polar Research, Polar research, a survey, 204 pp., National Research Council, National Academy of Sciences, Washington, D.C., 1970.

Meier, M. F., Evaluation of ERTS imagery for mapping and detection of changes of snowcover on land and on glaciers, in Proceedings of the Symposium on Significant Results Obtained from ERTS-1, NASA SP-327, vol. 1, pp. 863-875, U.S. Government Printing Office, Washington, D.C., 1973.

Rooney, J., The economic and social implications of snow and ice, in Water, Earth, and Man, pp. 389-401, edited by R. J. Chorley, Methuen and Company, Ltd., London, 1969.

Salomonson, V. V., and N. H. MacLeod, Nimbus hydrological observations over the watersheds of the Niger and Indus Rivers in 4th Annual Proceedings, Earth Resources Review, vol 1, pp. 5-1 to 5-11, NASA Document MSC 05937, Manned Spacecraft Center, Houston, 1972.

U. S. Department of Interior, Project Skywater, Bureau of Reclamation, Atmospheric Water Resources Program, 16 pp., U. S. Goverment Printing Office, Washington, D. C., 1970.

U. S. Department of Interior, Snow mapping and runoff forecasting: Examination of ERTS-1 capabilities and potential benefits from an operational ERS system, Interim Report, Contract No. 14-08-001-13519, Office of Economic Analysis, Washington, D. C., 1974.

Wiesnet, D. R., and D. F. McGinnis, Snow-extent mapping and lake ice studies using ERTS-1 MSS together with NOAA-2 VHRR, in Proceedings of the Third ERTS-1 Symposium, NASA SP-351, Vol. 1, pp. 995-1009, U. S. Government Printing Office, Washington, D. C., 1974.

Table 1
Wind River Mountains Multispectral Comparison of
Percent of Basin Snowcovered,
Band 5 (0.6–0.7μm) vs Band 7 (0.8–1.1μm)

1973						
	May 21		June 8		June 25-26	
	Band 5	Band 7	Band 5	Band 7	Band 5	Band 7
Bull Lake Creek	86%	85%	58%	56%	53%	46%
Dinwoody Creek	80%	78%	61%	56%	49%	43%
Pine Creek	93%	88%	80%	76%	70%	62%
Big Sandy River	71%	66%	23%	21%	19%	15%
East Fork River	91%	90%	40%	39%	24%	21%
Wind River	41%	39%	16%	11%	Cloudy	
Green River	55%	49%	27%	23%	Cloudy	
1974						
	May 16		June 2-3		June 21	
	Band 5	Band 7	Band 5	Band 7	Band 5	Band 7
Bull Lake Creek	89%	89%	79%	78%	57%	51%
Dinwoody Creek	85%	84%	76%	76%	56%	46%
Pine Creek	96%	95%	93%	90%	78%	71%
Big Sandy River	76%	73%	45%	41%	21%	18%
East Fork River	87%	83%	74%	66%	29%	25%
Wind River	67%	63%	Cloudy		23%	*
Green River	86%	85%	Cloudy		34%	31%

*Contrast in this band is not suitable for snow mapping.

Table 2
Comparison of Snow Extent Obtained From LANDSAT-1 and U-2 Sensors
Over Three High Elevation Watersheds in the
Wind River Mountains of Wyoming

Watershed	Data Source	Date	Snow Extent in Percent of Basin
1) Bull Lake Creek	LANDSAT-1	16 May 74	89
Bull Lake Creek	U-2	24 May 74	88
Bull Lake Creek	LANDSAT-1	21 June 74	57
Bull Lake Creek	U-2	25 June 74	60
2) Dinwoody Creek	LANDSAT-1	16 May 74	85
Dinwoody Creek	U-2	24 May 74	84
Dinwoody Creek	LANDSAT-1	21 June 74	56
Dinwoody Creek	U-2	25 June 74	60
3) Pine Creek	LANDSAT-1	21 June 74	78
Pine Creek	U-2	25 June 74	82

LIST OF FIGURES

Figure 8. LANDSAT-1 derived snowcover estimates versus measured runoff (1973 and 1974) for four watersheds less than 3,050 m mean elevation in the Wind River Mountains, Wyoming.

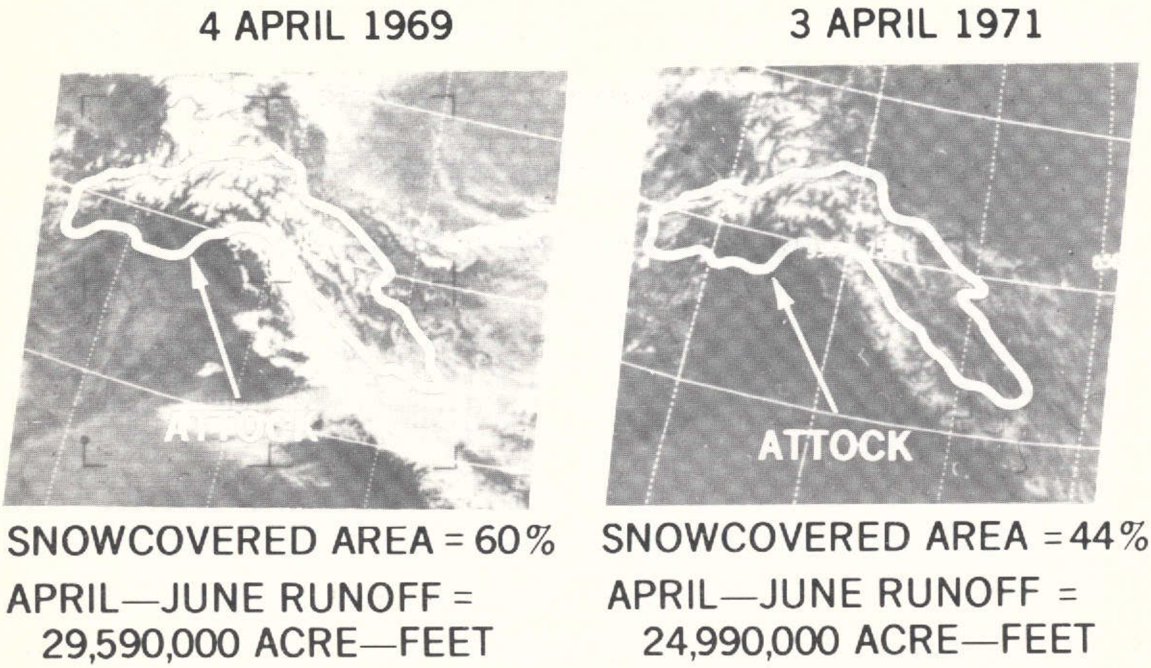

Figure 1. ESSA 9 observations of the annual variation in snowcovered area at the beginning of snowmelt in the Indus River Basin above Attock, Pakistan.

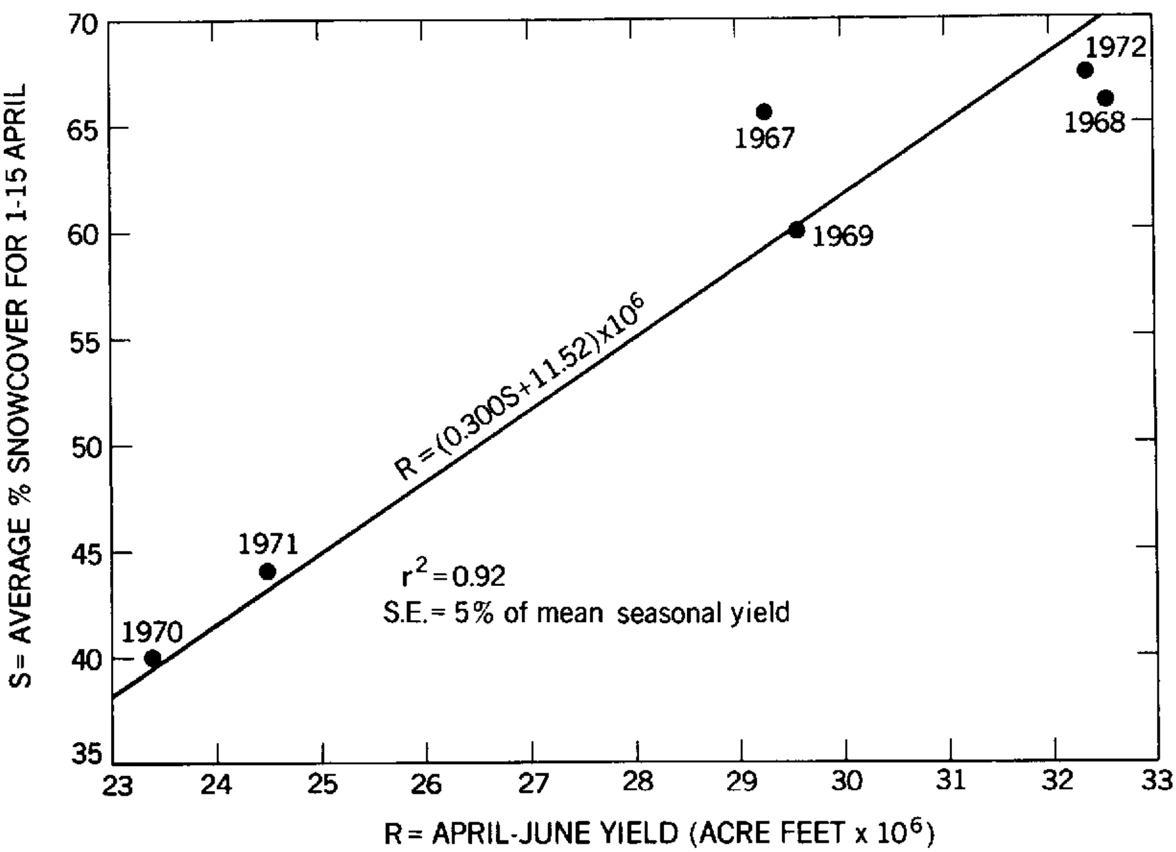

Figure 2. Satellite-derived snowcover estimates versus measured runoff for the Indus River, 1967-1972.

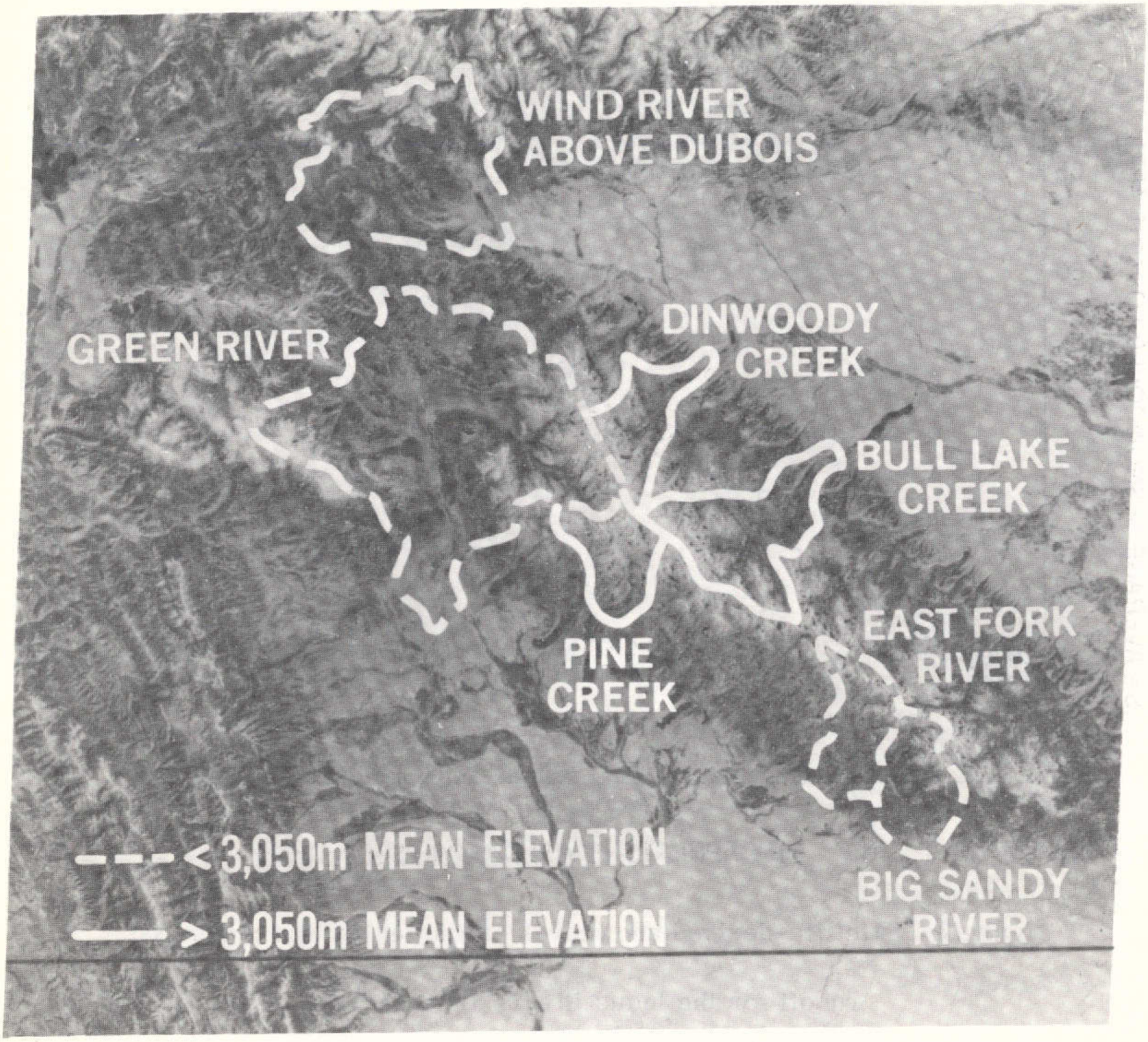

Figure 3. LANDSAT-1 0.6–0.7 μm view of the Wind River Mountains of Wyoming, 6 August 1972. The boundaries of the seven watersheds used in the LANDSAT-1 snowcover depletion-runoff analysis are indicated.

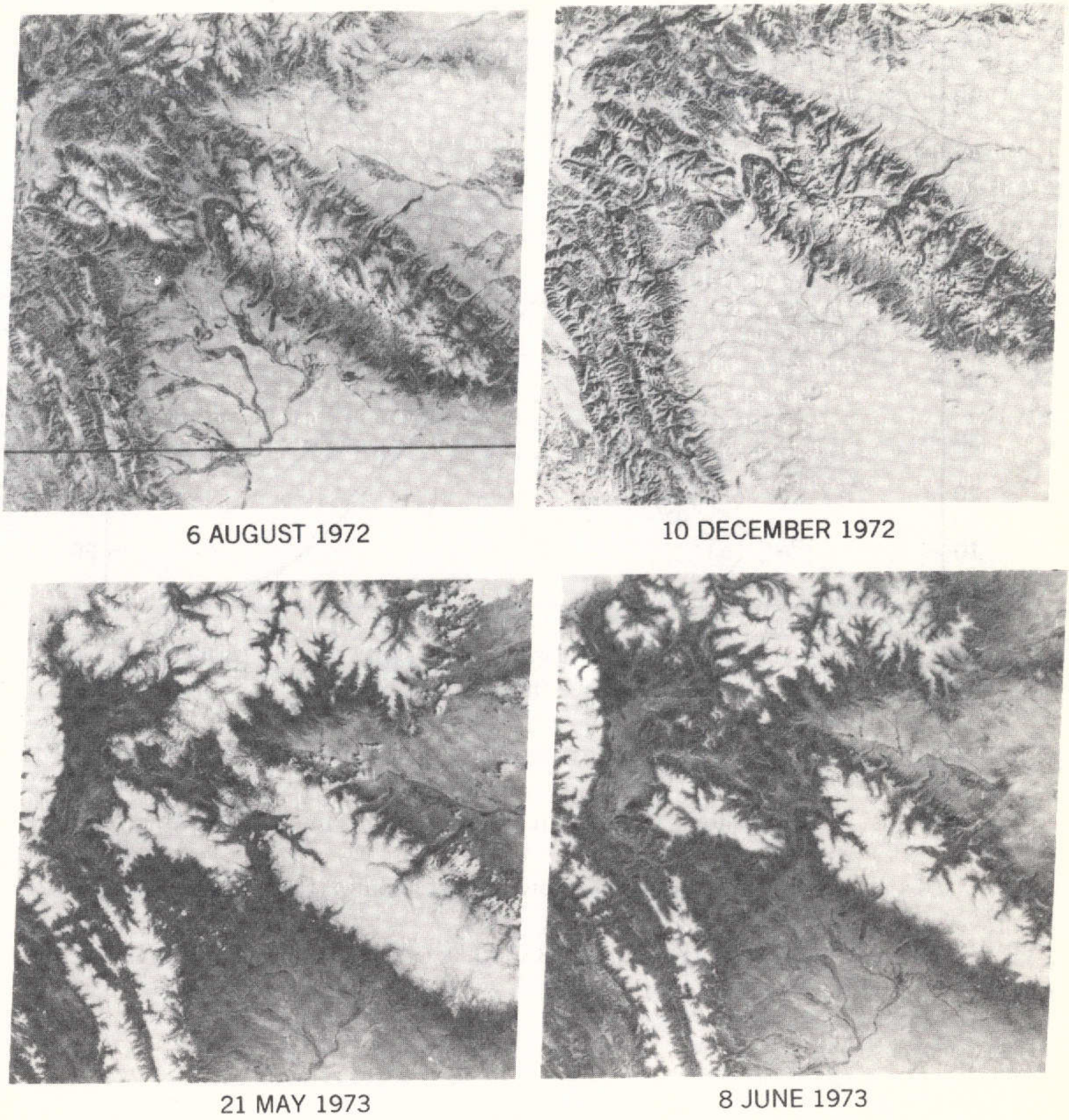

Figure 4. Snowcover changes in northwestern wyoming, 1972-1973.

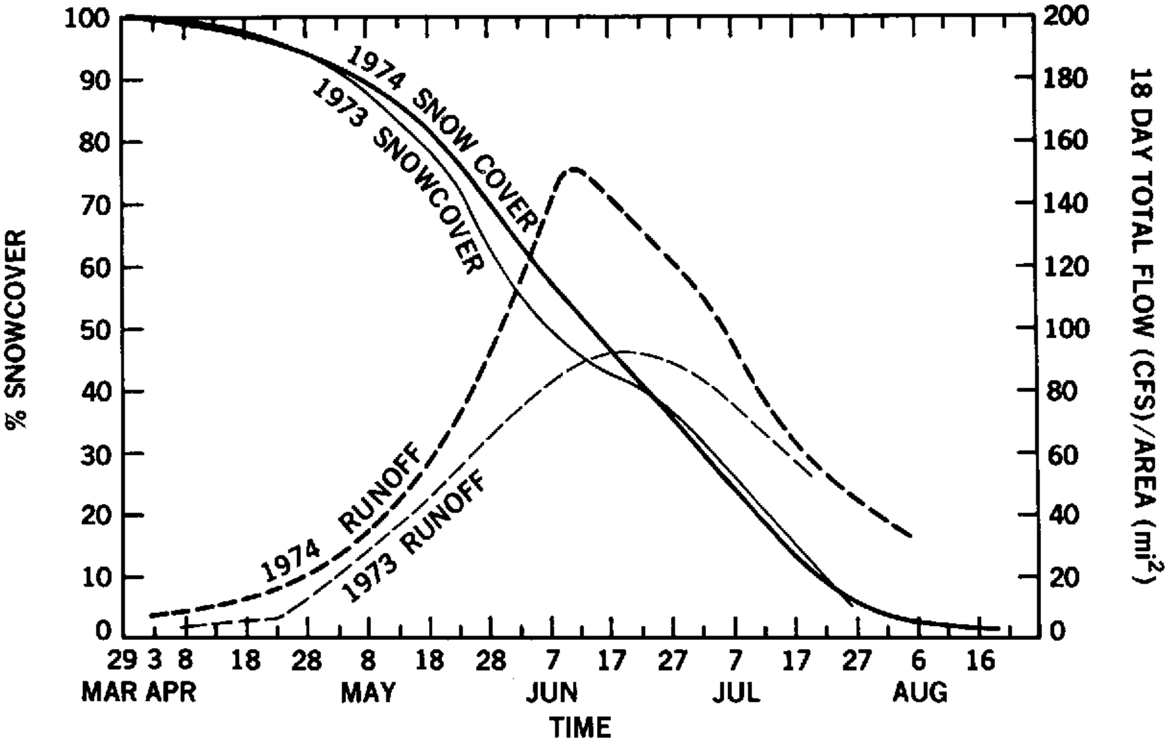

Figure 5. Average snowcover depletion and runoff curves for seven watersheds in the Wind River Mountains of Wyoming for the 1973 and 1974 snowmelt seasons. Snowcover area obtained from LANDSAT-1 0.6–0.7 μm observations.

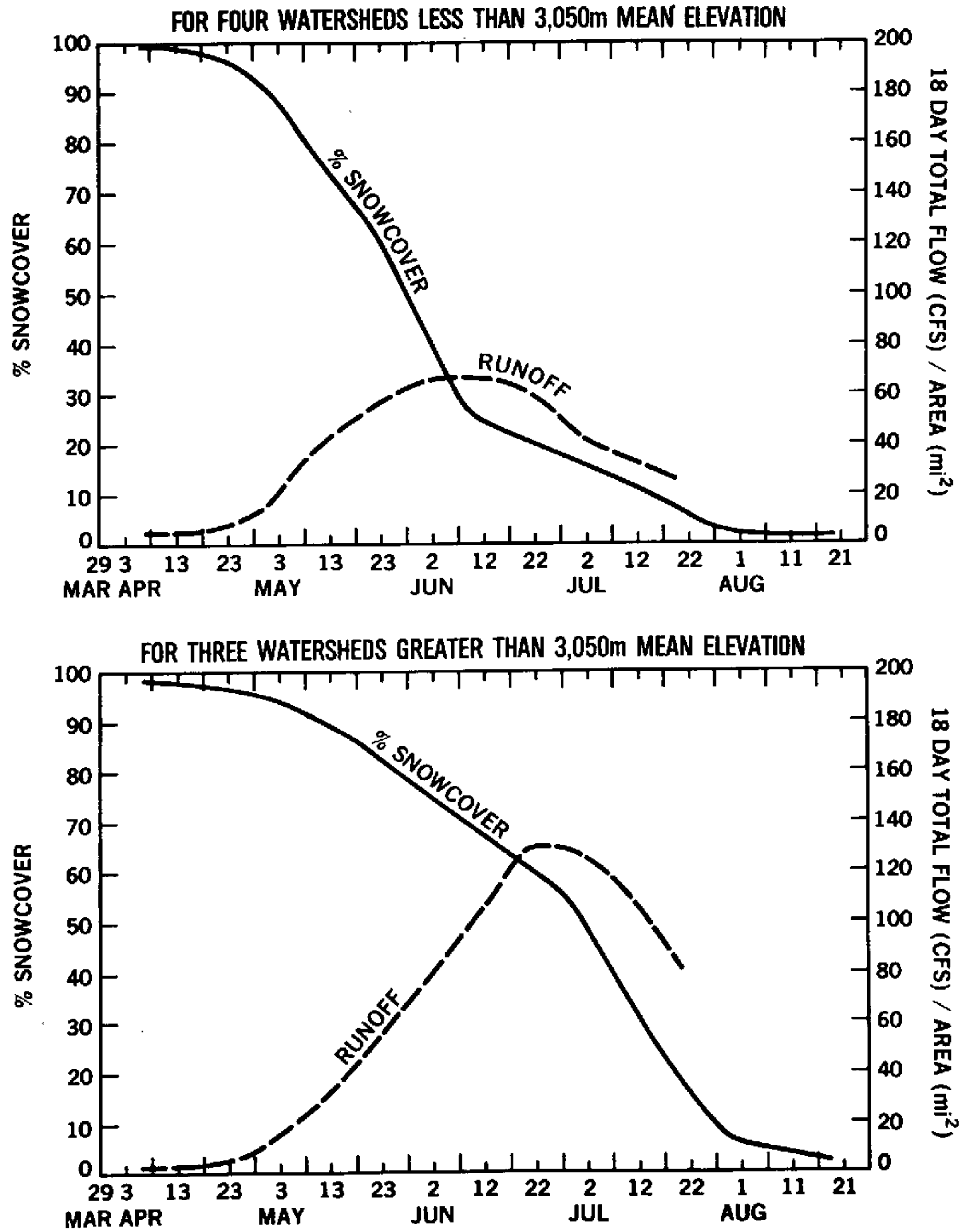

Figure 6. 1973 average snowcover depletion and runoff curves for the Wind River Mountains, separated on the basis of mean elevation. Snowcover area obtained from LANDSAT-1 0.6–0.7 μm observations.

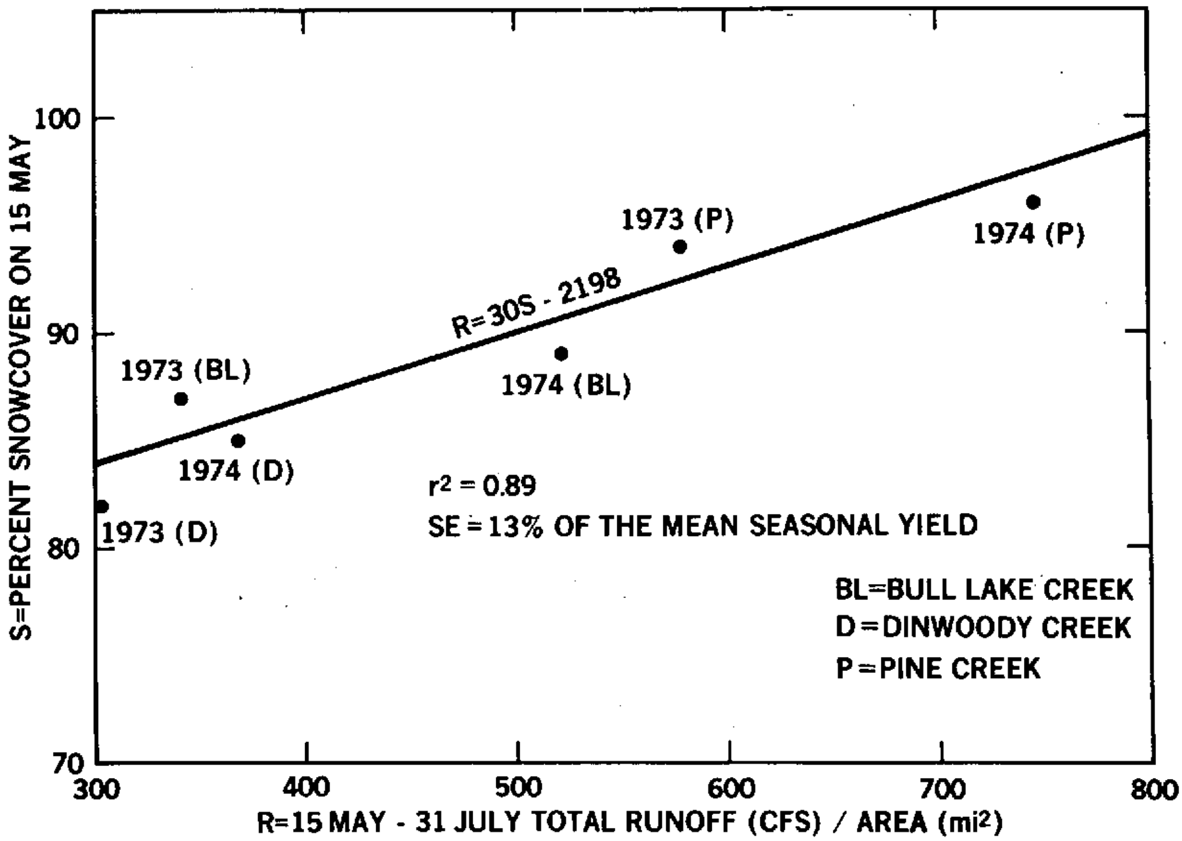

Figure 7. LANDSAT-1 derived snowcover estimates versus measured runoff (1973 and 1974) for three watersheds greater than 3,050 m mean elevation in the Wind River Mountains, Wyoming.

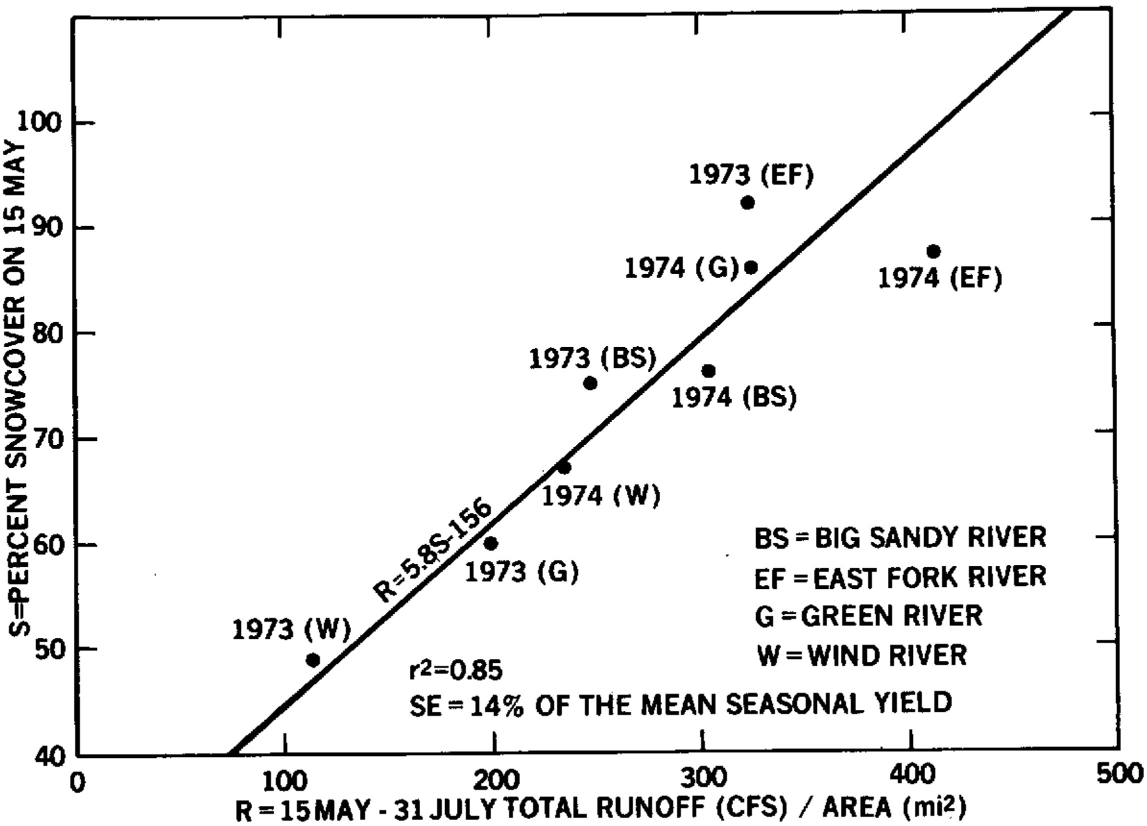

Figure 8. LANDSAT-1 derived snowcover estimates versus measured runoff (1973 and 1974) for four watersheds less than 3,050 m mean elevation in the Wind River Mountains, Wyoming.